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NOTE

The purpose of this grant was to support the research efforts of Dr. Mary Altalo under the Scientific Personnel Research Program. Due to the team's inability to acquire adequate amounts of field and satellite data for characterizing spatial and temporal variability of phytoplankton blooms in coastal waters, Dr. Altalo agreed with the research team to change the direction of this research to investigate Delaware Bay tidal parameters from space shuttle photography. Our final report consists of the paper entitled "Derivation of Delaware Bay Tidal Parameters from Space Shuttle Photography," published in *Remote Sensing of Environment*, 44:1-10 (1993).

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Derivation of Delaware Bay Tidal Parameters from Space Shuttle Photography

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The tide-related parameters of the Delaware Bay are derived from space shuttle time-series photographs. The water areas in the bay are measured from interpretation maps of the photographs with a CALCOMP 9100 digitizer and ERDAS Image Processing System. The corresponding tidal levels are calculated using the exposure time annotated on the photographs. From these data, an approximate function relating the water area to the tidal level at a reference point is determined. Based on the function, the water areas of the Delaware Bay at mean high water (MHW) and mean low water (MLW), below 0 m, and for the tidal zone are inferred. With MHW and MLW areas and the mean tidal range, we calculate the tidal influx of the Delaware Bay, which is 2.76×10^9 m^3. Furthermore, the velocity of flood tide at the bay mouth is determined using the tidal flux and an integral of the velocity distribution function at the cross section between Cape Henlopen and Cape May. The result is 132 cm/s, which compares well with the data on tidal current charts.

INTRODUCTION

The Delaware Bay, as a semienclosed water body connecting with the ocean, is a unique unit of coastal oceanography. Its evolution is strongly influenced by the ocean, the river discharge, and the surrounding land. Siltation, beach erosion, sand bar growth at inlets, and pollution are common phenomena in a bay. These processes cause damages to navigation channels, harbors, and coastal facilities, as well as gradual changes in the ecosystem. Therefore, monitoring the bay dynamically is of significance to scientific research and engineering applications. For this purpose it is necessary to collect local measurements and observations of various parameters. To obtain these data, ship-board observations are traditionally used. However, they are costly and sometimes difficult to perform in the tidal zone. As a complement or partial replacement, satellite remote sensing is an efficient and economic way.

Mapping is a fundamental application of satellite images as with aerial photographs. Its unique value is to provide a synoptic view and dynamic conditions of the coastlines of the bay for planning, decision making, engineering, and research. For dynamic studies of the water body in the bay, the visible band images which are sensitive to the changes in water color have been extensively used to observe the distribution of suspended sediment, and using the sediment as a natural tracer, the tidal flow patterns in the surface layers have been deduced (Klemas et al., 1973). Similarly, the position of small frontal structures in the bay could be examined, which influence pollutant dispersal (Klemas, 1980). Landsat MSS (Multispectral Scanner) and TM (Thematic Mapper) images

have also been used to detect submerged aquatic vegetation within the Guinea Marsh area of Lower Chesapeake Bay (Ackleson and Klemas, 1987). Combining with tidal data, the high resolution satellite images, for example, Landsat TM images, have been used to calculate the dynamic parameters of the day (Zheng et al., 1992).

The hand-held photography taken by the flight crew on the manned spacecrafts as a special sort of spaceborne remote sensing imagery has proven its worth for studies of coastal oceanography during the Gemini and Apollo (Mairs, 1970; Soules, 1970), Skylab (Klemas et al., 1974), and Apollo–Soyuz (Maul, 1978) projects in the 1970s. Since 1981 the United States has performed Space Shuttle missions. After 10 years of operations, a Space Shuttle Earth Observations Project (SSEOP) database having approximately 77,000 hand-held photographs of the Earth has been set up. Among the photographs, about 75% represent the globally distributed coastal zone. The database has recently been made easily accessible to the research community (Ackleson, 1992). In this study new data sets of hand-held photographs taken by the astronauts of the Space Shuttle Columbia are used as a basic database to derive the tide-related parameters of the Delaware Bay. Development of a methodology which can provide quantitative results is emphasized. Delaware Bay is taken as an example, like a training site for image processing, because the historical data base and research results are available for reference.

GEOGRAPHIC OUTLINE OF DELAWARE BAY

The Delaware Bay is located between 38°45'–39°30'N and 74°50'–75°40'W, which is on the east coast of the United States facing the Middle Atlantic Bight. The bay as a part of the Delaware River Estuary is bounded on both sides by the states of Delaware and New Jersey, respectively. The downstream boundary of the bay extends from Cape Henlopen, Delaware to Cape May, New Jersey. The upstream boundary of the bay, however, is defined with the different geographic reference points. Some previous investigators have used the Smyrna River (Schuster, 1959) or the southern tip of Artificial Island (Zeskind and LeLacheur, 1926) as the upstream limit of the

bay. But the legal definition of the upstream boundary is a line between the stone markers at Liston Point, Delaware and Hope Creek, New Jersey (Polis and Kupferman, 1973). In this article, we use the legal definition as the boundary between the bay and the river as shown in Figure 1.

The morphology and bathymetry of the bay have been extensively surveyed. The length of the bay is about 75 km, and the width varies from 18 km at the mouth to about 45 km at the widest point. Maximum depth in the bay is about 45 m and the mean depth is about 10 m, while 90% of the bay is less than 18 m deep. The total surface area of the bay is about 1864 km^2, and the total length of the shoreline is about 260 km (Polis and Kupferman, 1973; Pape, 1981). There are deep navigation channels throughout the bay which connect the harbors of Wilmington, Delaware, Philadelphia, Pennsylvania, and Trenton, New Jersey with the Atlantic Ocean, so that transport of oil and other goods is an important industry.

The tide in the bay is dominated by the semi-diurnal constituent having a period of 12.42 h. The mean range of the tide is about 1.3 m at the capes, and generally increases throughout the bay to about 1.7 m at Liston Point, which is the upstream limit of the bay. According to calculations by Polis and Kupferman (1973), the total ebb transport is 4.33×10^9 m^3, and the total flood transport is 4.06×10^9 m^3.

The Delaware River is the main fresh water source discharging into the bay. The average river discharge over a tidal cycle is 0.024×10^9 m^3 (Polis and Kupferman, 1973).

SPACE SHUTTLE PHOTOGRAPHS

The space shuttles are equipped with a NASA modified Hasselblad 500 EL/M 70-mm camera. On some flights, when mission plans permit, an Aero Linhof Technika 45 camera is carried. With these hand-held cameras the shuttle astronauts have taken photographs of interesting geophysical events around the world including oceanographic phenomena. Among them are many high quality photographs of the coasts, estuaries and bays. (UCAR and ONR, 1989; Ackleson, 1992; Evans and Duncan, 1991).

The space shuttle photographs have some obvious advantages for coastal application. First of
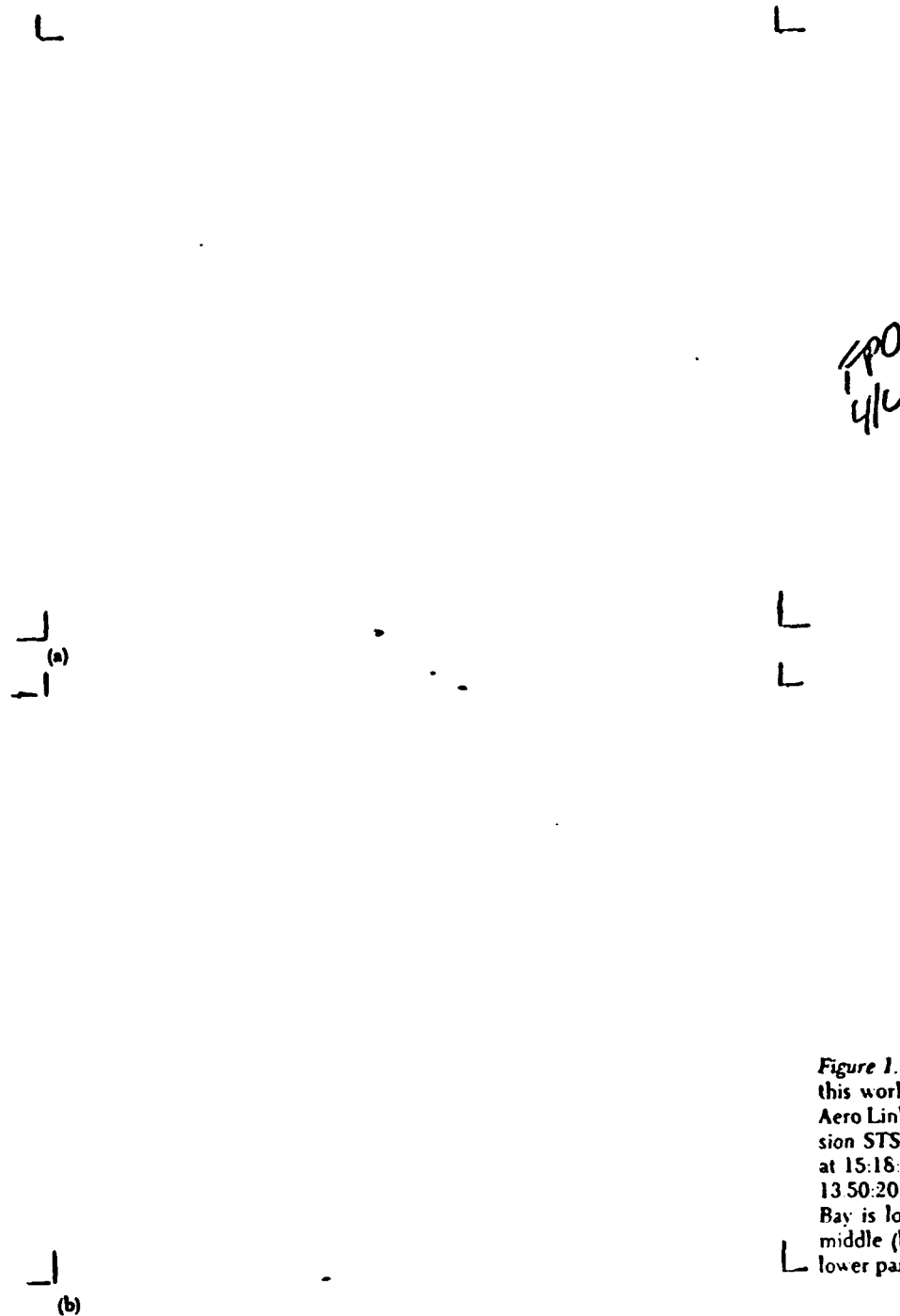
Figure 1. Space shuttle photographs used in this work taken by the astronauts with the Aero Linhof Technika 45 Camera during Mission STS 40 of the Space Shuttle Columbia at 15:18:24 GMT on 8 June 1991 (a) and at 13 50:20 GMT on 10 June 1991 (b). Delaware Bay is located at the upper middle (a) and middle (b) portions. The bright spot on the lower part of the photographs is the sunglint.

all, they have high spatial resolution. For the photographs used in this article the spatial resolution at the nadir is as high as 23 m calculated for an orbit altitude of 196 km (LaViolette et al., 1991), which is better than 30 m for Landsat TM (Thematic Mapper) images, and much better than 1 km AVHRR (Advanced Very High Resolution Radiometer) images of the NOAA (National Oceanographic and Atmospheric Administration) series satellites, which are frequently used in oceanographic studies. The second advantage of space shuttle images is high repeatable observation frequency, which can reach once a day for a short period. That provides a good opportunity for time-series measurement and analysis for tide-related phenomena and other processes with these time scales. The third advantage is high geometric accuracy. The optical system of the Linhof camera

is originally designed for aerophotography, which requires high geometric accuracy for mapping and survey purposes. There is little distortion in the central part of the photographs compared with standard geographic maps.

The photographs used in this paper were taken with the Aero Linhof Technika 45 camera, which is equipped with a 250 mm Tele-Arlon 5.6 lens. The raw data are the positive color films with a size of 4×5 sq in., which are dated 8 and 10 June 1991 during mission STS-40 of the Space Shuttle Columbia and are shown in Figure 1. The photographs are centered on Delaware Bay, and cover most of the coast of New Jersey, the Delmarva peninsula, and the Chesapeake Bay, as well as their adjacent continental shelf on the Middle Atlantic Bight. By enlarging the films into photographs with sizes 30 in. $\times$ 40 in. and 16 in. $\times$ 20 in., the basic images for mapping and surveying are produced. The specifications of the photographs are summarized in Table 1.

TIDAL PARAMETERS OF DELAWARE BAY

Tidal Influx

The tidal influx is a significant parameter for a tidally dominated bay, maintaining the lifeblood of a bay. A decrease of the tidal influx implies that the tidal circulation is becoming weaker, the sedimentation rate is becoming higher, and eventually the bay will be silted in. Furthermore,

the navigation channels will be damaged, and the ecosystem in the bay will be changed too. Therefore, it is important to measure or to monitor the change in the tidal influx of a bay.

According to the definition of the dynamics of a bay, the tidal influx W_b is calculated by

$$W_b = (S_1 + S_2)H/2, \tag{1}$$

where S_1 and S_2 are the water areas corresponding to mean high water (MHW) and mean low water (MLW), respectively, and H is the mean tidal range, that is, the difference in height between the two. This is a universal formula regardless of coastal geometry and bottom topography of the bay.

From Eq. (1), one can see that if S_1, S_2, and H are known, the tidal influx, W_b, can be calculated. Usually H can be found in the tide tables, and the areas S_1 and S_2 must be measured either with a field survey or with remote sensing. Field surveys, however, hardly obtain synchronous data for a huge bay because of the changeable tide levels. Satellite remote sensing can provide synchronous imagery for a large bay, which can be used to map and to measure the water area. But the time of the satellite overpass rarely coincides with the required tide stage. In order to derive the water area at a given tide stage, it is necessary first to determine a function relating the water area to the tide level at a reference point. We assume that this function, $A(h)$, has the form of a power series:

$$A(h) = \sum_{n=0}^{\infty} k_n h^n, \tag{2}$$

where the variable h is the tide level at the reference point and k_n the coefficient to be determined. Obviously, the water areas measured from satellite images, the exposure times, and the tide tables can be used to obtain k_n, and the functional form of $A(h)$ can be determined. Then the water area of the bay at any tide level can be simply calculated. The accuracy of $A(h)$ determined by Eq. (2) depends on the highest order of h, n. If we have two groups of data of the water area and their corresponding tide levels, the coefficients k_0 and k_1 are obtained by solving coupled equations, and a linear equation of $A(h)$ can be determined as a first-order approximation.

For this study, we chose two photographs from the Space Shuttle, which are coded 910608 151824 STS40-LN1IF-15 and 910610 135020

Table 1. Specifications for the Space Shuttle Photographs Used in This Work

Mission	STS-40
Platform	
Space shuttle	Columbia
Flight dates	5-14 June 1991
Orbit altitude (km)	287
Inclination (degree)	39
Sensor	
Camera	Aero Linhof Technika 45
Lens	250 mm Tele-Arlon 5.6
Incidence angle (deg)	0
Film	
Type	Kodak color transparency (QX 868)
Sensitive spectrum	Visible
Resolution (lines/mm)	50
Size of a scene (sq in.)	4 × 5
Photographing time	8 and 10 June 1991
Spatial resolution (m)	23 (nadir)

STS40-LNHF-151-162, as shown in Figures 1a and 1b, respectively, to determine the function of $A(h)$ for Delaware Bay. In these two photographs, the Delaware Bay is located near the central parts, and the geometric distortion of the imagery of the bay is relatively small; therefore, the measurement error due to this distortion is not significant. With the enlarged photographs, we prepared the interpretation maps of the water areas in the Delaware Bay. The definition of the bay is as follows: The line between Liston Point, Delaware, and Hope Creek, New Jersey, is defined as the upstream limit of the bay, while that between the tips of Cape Henlopen and Cape May as the downstream one, and the two sides of the bay are bounded by the boundaries of the sea water at exposure time. The scales of the interpretation maps are determined using four reference points distributed on the two coastal sides of the bay. The distance between the two reference points across the bay is derived from the Atlantic Coast map with a scale of 1:1,200,000 at Lat. 40°00'N published by the NOAA National Ocean Survey in 1975. Then the water areas are measured from the interpretation maps with a CALCOMP 9100 digitizer and ERDAS Image Processing System. The resolution of this system is 0.01 cm^2, and the measured areas in the images are about 30 cm^2; therefore, the measurement errors are negligible. For each map we made measurements three times. The mean and the standard deviation are

$$A(h_1) = (1720 \pm 5)\ \text{km}^2$$
for the 910608 photograph

and

$$A(h_2) = (1776 \pm 3)\ \text{km}^2$$
for the 910610 photograph.

Breakwater Harbor, located at the inside of Cape Henlopen (38°47'N, 75°06'W), is chosen as a reference point for the tide level because it is the only station in the Delaware Bay for which the data are available in the Tide Tables. The height of tide at exposure time is calculated according to the method given in Table 3 of the Tide Tables (U.S. Dept. of Commerce, NOAA/ NOS, 1990). Before the calculation was performed, the exposure times in GMT annotated on the photographs were first transformed into the local time which is used in the Tide Tables. For the 910610 image, the local exposure time is 10:18:24 ET, and the tide level, h_1, is 6 cm; for the 910610 image, 8:50:20 ET, and h_2, 99 cm.

Substituting the values of $A(h_i)$ and h_i into Eq. (2), we obtain a linear function of the water area in the Delaware Bay versus the tide level at the Breakwater Harbor:

$$A(h) = k_1 h + k_0 \quad (\text{km}^2), \qquad (3)$$

where $k_1 = 0.60\ \text{km}^2/\text{cm}$ and $k_0 = 1717\ \text{km}^2$.

From the levels of high and low water at the Breakwater Harbor listed in the Tide Tables, we derive that the level of MLW is 3 cm, and that of MHW is 131 cm. Substituting these heights (levels) into Eq. (3), we have $S_1 = 1796\ \text{km}^2$ and $S_2 = 1719\ \text{km}^2$.

The mean tidal range, H, in Eq. (1) cannot be replaced directly with the values at Breakwater Harbor because it is variable along the coast. We chose nine tidal stations which are generally uniformly distributed along both sides of the bay and coded by 1, 2, 3, 4, 9, 10, 11, 12 and Cape May Point shown in Figure 2 to take the average of the mean tidal ranges. The geographic positions and the mean tide ranges of these stations are listed in Table 2, the data are taken from historical investigations at the University of Delaware. We obtain the average $H = 1.57$ m. Substituting S_1, S_2, and H into Eq. (1), the tidal influx into Delaware Bay, W_b, is derived as

$$2.76 \times 10^9\ \text{m}^3.$$

The uncertainty or error of this value is dependent on the accuracies of S_1, S_2, and H. We believe that the reasonable estimation is better than 3%, which is mainly caused by the interpretation error.

Tidal Zone Area

As a first-order approximation, Eq. (3) can be used to calculate the area of the bay at any tide stage. As an example, we calculate the area of the tidal zone in Delaware Bay. Checking the Tide Tables, we find that the highest high water and the lowest low water at Breakwater Harbor in a year are 174 cm and −27 cm, respectively. With Eq. (3) their corresponding water area is calculated as 1821 km^2 and 1701 km^2, respectively. Based on that, we obtain the area of the tidal zone in Delaware Bay:
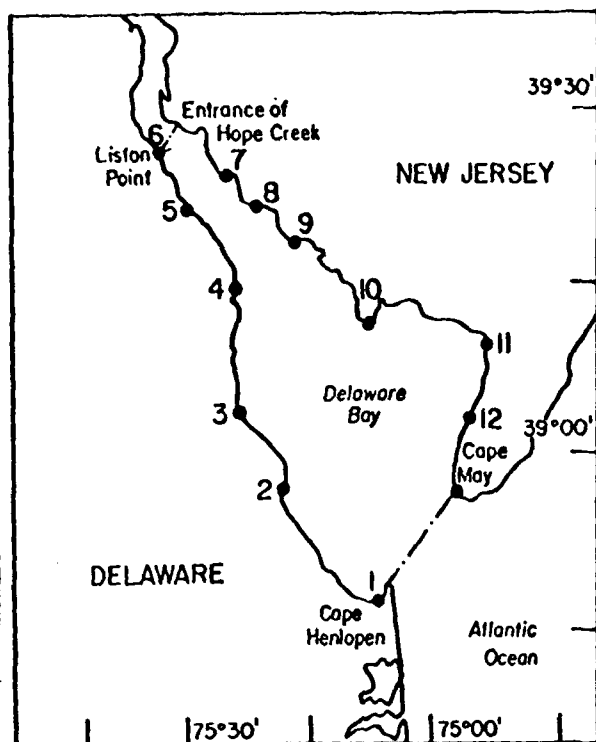
Figure 2. Interpretation map of the Delaware Bay drawn from the space shuttle photograph shown as Figure 1a. The upstream and the downstream limits of the bay used in this work are drawn with the dash and dot lines. The solid circles coded along the coastlines are the tidal stations, for which historical data are available.

$$A_{int} = 120 \text{ km}^2.$$

Area below 0 m

If we let H in Eq. (3) be zero, we obtain the area below 0 m depth for Delaware Bay, which is another important parameter for a tidal bay

$$A_0 = 1717 \text{ km}^2.$$

This parameter characterizes the basic and stable part of the bay. If this parameter is getting smaller, that means that the bay is silted in.

Velocity Amplitude of the Flood Tide at the Bay Mouth

The distribution of tidal velocity along the cross section at the bay mouth is usually used to calculate the total volume transported (e.g., Polis et al., 1973). But since we know the total volume transported, the cross-sectional topography at the mouth, and the functional form of tidal velocity, the velocity amplitude of flood or ebb tides can

Table 2. Tidal Stations Used for Calculation of the Mean Tidal Ranges of the Bay

Code	Place	Position	Mean Tide Range (m)
1	Breakwater Harbor	N38°47′, E75°06′	1.25
2	Mispillion River entrance	N38°57′, E75°19′	1.40
3	Murderkill River entrance	N39°04′, E75°24′	1.46
4	Leipsic River entrance	N39°15′, E75°24′	1.71
9	Ben Davis Point	N39°17′, E75°17′	1.83
10	Egg Island Point	N39°11′, E75°08′	1.74
11	Dennis Creek entrance	N39°10′, E74°54′	1.71
12	Miami Beach	N39°02′, E74°56′	1.56
	Cape May Point	N38°56′, E74°58′	1.43
Average			1.57

be inverted. In principle, the total tidal influx of an estuary, W, must be balanced with the total volume transported into the bay, at the bay mouth, Q, and the discharge of rivers into the estuary, Q_r, over the duration of flood or ebb tides, that is,

$$W = Q + Q_r \qquad (4)$$

where W contains two parts: the tidal influx of the bay, W_b, and that of the rivers, W_r, and $Q_r/Q = 1/226$ for the Delaware Bay (Garvine, 1991), so that Q_r can be ignored as compared to Q. Then we have

$$W_b + W_r = Q. \qquad (5)$$

For Delaware Bay, we have derived $W_b = 2.76 \times 10^9 \text{ m}^3$ from the space shuttle photographs and the tidal data in the second section. The tidal influx of the Delaware River can then be calculated with the total area of 171 km² by using the mean tidal range of 1.68 m (Polis et al., 1973), that is, $0.29 \times 10^9 \text{ m}^3$. The influx of other rivers can be ignored, because their total volume is much smaller than that of the Delaware River. Therefore, W_r is approximately $0.29 \times 10^9 \text{ m}^3$, and $3.05 \times 10^9 \text{ m}^3$ should be a good estimation of the total tidal influx of the Delaware Estuary.

The total volume transported into the bay at the bay mouth during the duration of the flood tide, Q, can be calculated with an integral

$$Q = \int_0^{T_1} \int_0^{B_{(t)}} \int_0^L V(x,z,t) \, dx \, dz \, dt, \qquad (6)$$

where the coordinate system is determined so that the origin is at the tip of the left cape at the bay mouth (for our case, the Cape Henlopen), the

X-axis goes along the line between the capes, the rightward is positive, the Z-axis is perpendicular to the X-axis, the upperward positive; $V(x,z,t)$ is the tidal velocity at an arbitrary point on the vertical section at the bay mouth at any tidal stage; the integral limit $B(x)$ for Z is a function of bottom topography, L for x is the width of the bay mouth, T_1 for t is the duration of flood tide.

The integrand, tidal velocity $V(x,z,t)$, in general, can be expressed as

$$V(x,z,t) = \sum_v V_v(x,z) \cos(\sigma_v t + \kappa_v), \quad (7)$$

where σ_v and κ_v are the angular speed and initial phase of the μ partial tide. The dominant tide in the Delaware Bay is semidiurnal; the diurnal constituents are relatively small. To simplify the calculation, we modify Eq. (7) into an approximate form

$$V(x,z,t) = V(x,z) \cos 2\pi t / T, \quad (8)$$

where T is the period of the semidiurnal tide, that is, 12.42 h, and the functional form of $V(x,z)$ can be determined with an analysis of the field data. For a bay mouth with strong tidal flow like the

Delaware Bay, the bottom friction can be ignored. $V(x,z)$ can be considered to be independent of z as shown in Figure 3, and $V(x)$ can be written as (see Polis et al., 1973, Table XIV)

$$\begin{aligned}
V(x) &= v && \text{for } 0 < x < 0.37, \\
&= 0.90v && \text{for } 0.37 < x < 0.52, \\
&= 0.85v && \text{for } 0.52 < x < 1, \quad (9)
\end{aligned}$$

where the three function ranges are shown in Figure 4.

In order to calculate the integral on the right-hand side of Eq. (6), the limits of integration must first be determined. The upper limit of t, T_1, is the duration of flood tide, that is, 6.6 h for the Delaware Bay, longer than the half period of the semidiurnal tide. The upper limit of z, $B(x)$, is a function of the bottom at the Delaware Bay mouth. The bottom topography between Cape Henlopen and Cape May is shown as solid lines in Figure 4 (after Fig. 30, Polis et al., 1973), and divided into three parts, which are fit with three different functions:

$$\begin{aligned}
B(x) &= B_1 = 25(x - 0.2)^2 - 1 && \text{for } 0 < x < 0.37, \\
&= B_2 = -0.4 && \text{for } 0.37 < x < 0.52, \\
&= B_3 = 6.4(x - 0.75)^2 - 0.4 && \text{for } 0.52 < x < 1, \\
&&& \quad (10)
\end{aligned}$$

where x is normalized with respect to the width of the section, L, and z with respect to the depth of the top of the first parabola, D ($= 27.3$ m). The upper limit of x, L, is the width of the bay mouth, that is, 20 km.

Substituting the integrand and the limits of integration into Eq. (6) and noting that the variable x and z are normalized with L and D, we have

$$Q = 2DLv \int_0^{T/2} \cos \frac{2\pi t}{T} dt$$

$$\times \left[\int_0^{0.37} B_1(x) \, dx + 0.90 \int_{0.37}^{0.52} B_2(x) \, dx \right.$$

$$\left. + 0.85 \int_{0.52}^{1} B_3(x) \, dx \right]. \quad (11)$$

Calculating this integral and substituting the result into Eq. (5), we obtain

$$v = 132 \text{ cm/s}.$$

According to the definition of tidal influx of a bay, Eq. (1), we know that this value is equivalent to the maximum velocity of neap flood tide.

Figure 3. Vertical profiles of normalized maximum flood velocity at the Delaware Bay mouth derived from *in situ* data. The Z-axis is the depth. B_1, B_2, and B_3 correspond to three parts of the bottom topography between Cape Henlopen and Cape May as shown in Figure 4.
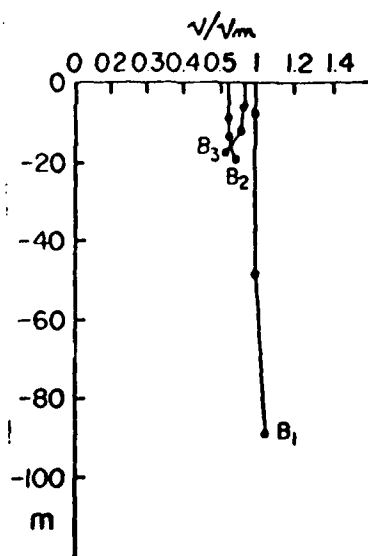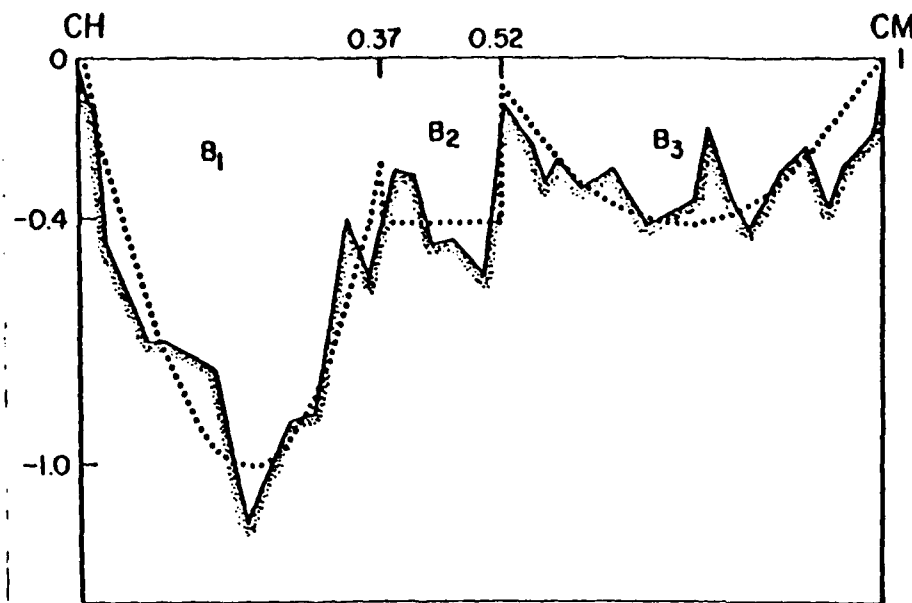
Figure 4. Bottom topography between Cape Henlopen and Cape May (solid lines) and fitting functions (dashed lines). The scales on the axes have been normalized with respect to the width of the bay mouth (X-axis) and the depth of the top of curve B_1 (Z-axis). CH: Cape Henlopen; CM: Cape May.

DISCUSSION

The results of this study indicate that space shuttle photographs are valuable for studying the bay and estuaries, not only qualitatively, but also quantitatively. High spatial resolution and small geometric distortion of the central parts of the photographs provide a satisfactory accuracy for bay-scale mapping and measurement. Exposure time and annotations on the photographs provide an important factor for calculating the coincident tide levels which are a dominant forcing process in a bay originating from the ocean. Combining these two directly measured parameters makes it possible to derive the tide-related parameters of the bay, which are necessary for research and monitoring, but not easily obtained with traditional field surveys.

We determined that the water area at the Mean High Water (MHW) of the Delaware Bay is 1796 km², which is smaller than the historical value of total surface area of 1864 km² or 720 sq miles (Polis et al., 1973). The reason is the different definitions for the bay. We use the legal definition of the bay which takes Liston Point as the upstream limit, and the line between the tips of Capes Henlopen and May as the downstream

limit of the bay, because these two reference points are easily recognized on the space shuttle photographs. The historical data has been calculated with the Smyrna River as the upstream limit and a fold line between Cape Henlopen and the southwest tip of Cape May as the downstream limit (see Fig. 3, Polis et al., 1973). The area of tidal zone of 120 km², and the area below the 0-m level of 1717 km² obtained in this article are new results.

The velocity amplitude of flood tide at the bay mouth of 132 cm/s, we obtained is comparable to the data published on Tidal Current Charts of Delaware Bay and River (U.S. Dept. of Commerce, NOAA/NOS, 1978), but about 10% higher than the data on the charts. The main reasons we think are as follows: The first error source is that the time for the tidal waves to travel from the bay mouth to the upper reach of the Delaware River is about 8 h, which is longer than the duration of flood tide of 6.6 h. That means that the volume transported into the estuary during the duration of flood tide would be smaller than the total tidal influx, $W_b + W_r$ in Eq. (5). Therefore, the velocity amplitude derived from Eq (5) would be higher. The second error source is that the functions describing the bottom topography is not exactly

fitted to the true topography. Even so, the results still verify that the methods developed in this paper work well.

The other potential factor which may have an influence on the parameters of the bay is wind. The unusually wind-driven current may cause a wind setup in the bay, which increases the water area and volume in the bay. This phenomenon may occur during a storm or persistent monsoon. For our case, we collect the buoy data taken from NOAA data buoy coded with station 44012, which is located at 38.8°N latitude and 74.6°W longitude and is closest to the Delaware Bay mouth. The data show that the wind speed varied from 0.3 m/s to 6.0 m/s, and the wind direction varied between SW and SE during 7-10 June 1991. Unfortunately, there are no models or figures available for Delaware Bay showing the relationship between the wind setup and the wind stress. For such low wind speeds, however, it is reasonable to ignore the influence of wind on the measurements in this study.

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